

## Observation of the Uller–Zenneck wave

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**Abstract.** The Uller–Zenneck wave has been theoretically predicted to exist at the planar interface of two homogeneous dielectric materials of which only one must be dissipative. Experimental confirmation of this century-old prediction was obtained experimentally by exciting the Uller–Zenneck wave as a Floquet harmonic of non-zero order at the periodically corrugated interface of air and crystalline silicon in the 400–to–900-nm spectral regime. Application for intra-chip optical interconnects at  $\sim 850$  nm appears promising.

A doctoral dissertation from 1903 predicted the existence of an electromagnetic surface wave (ESW) guided by the planar interface of air and seawater [1], followed four years later by a similar prediction for an ESW guided by the planar interface of air and ground [2]. Both theoretical predictions were made for the radiofrequency (RF) regime, the seawater and the ground being dissipative dielectric materials in that spectral regime. If  $\varepsilon_s$  is the relative permittivity of the dissipative dielectric material such that  $\text{Re}(\varepsilon_s) > 0$  and  $\text{Im}(\varepsilon_s) > 0$ , while  $k_0$  is the free-space wavenumber, then the wavenumber  $q$  of the Uller–Zenneck wave is given by

$$q = k_0 \sqrt{\varepsilon_s / (\varepsilon_s + 1)}, \quad (1)$$

where the relative permittivity of air is assumed to be unity. The same formula also holds for surface-plasmon waves [ $\text{Re}(\varepsilon_s) < 0$ ,  $\text{Im}(\varepsilon_s) > 0$ ] [3] and Fano waves [ $\text{Re}(\varepsilon_s) < 0$ ,  $\text{Im}(\varepsilon_s) = 0$ ] [4]. All three ESWs are  $p$  polarized, but the relative permittivity of the material partnering air satisfies different conditions for all three.

Controversy has surrounded the Uller–Zenneck surface wave for almost a century [5, 6] and RF experiments to excite it on a planar guiding interface have not provided unambiguous proof of its existence [6, 7]. The same ambiguity will prevail in other spectral regimes. However, if the guiding interface were to be periodically corrugated, theory has recently shown [8] that unambiguous proof could be experimentally obtained. As periodically corrugated interfaces are easily fabricated [9] for operation as diffraction gratings in the optical regime, we decided to experimentally confirm the existence of the Uller–Zenneck wave in this regime using a one-dimensional grating written by electron-beam lithography on a wafer of crystalline silicon. This communication reports our experimental results.

The theoretical foundation of the experiment undertaken is briefly recounted as follows: As shown schematically in Fig. 1(a), the regions  $z < 0$  and  $z > L_t = L_g + L_m$  are occupied by air, the region  $L_g < z < L_t$  is occupied by the dissipative dielectric material of relative permittivity  $\varepsilon_s$ , and the region  $0 < z < L_g$  contains a grating of period  $L$  along the  $x$  axis and duty cycle  $\zeta \in (0, 1)$ . Let a  $p$ -polarized plane wave be obliquely incident upon the grating. The wave vector of the incident plane wave lies wholly in the  $xz$  plane and is oriented at an angle  $\theta$  with respect to the  $z$  axis. The reflected ( $z \leq 0$ ) and the transmitted ( $z > L_t$ ) fields comprise Floquet harmonics of orders  $n \in \mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$ . Whereas  $n = 0$  identifies the specular components of the reflected and transmitted fields, the non-specular components are identified by  $n \neq 0$ . The rigorous coupled-wave approach (RCWA) [10, 11] is useful for computing the reflectances  $R_p^{(n)}$  and the transmittances  $T_p^{(n)}$  as functions of the angle of incidence  $\theta$  and the free-space wavelength  $\lambda_0 = 2\pi/k_0$ . The absorptance  $A_p$  can then be determined using the principle of conservation of energy [8].

For experiments, a  $7 \times 7$  mm<sup>2</sup> grating was fabricated on a 4-inch-thick silicon wafer as follows. The wafer was first spin-coated with ZEP520A photoresist (Zeon, Tokyo) diluted 1:1 with methoxybenzene. Next, the wafer was spun at 2000 rpm for 45 s and then baked at 180 °C for 180 s. The grating pattern was then written using the Vistec 5200 electron-beam lithographic system (Vistec, Best, The Netherlands). Thereafter, the photoresist was developed for 3 min at  $-12$  °C in  $n$ -amyl acetate, rinsed with isopropyl alcohol (IPA) for 30 s at 20 °C, and dried using blowing nitrogen. Dry etching was done next on a Versalock 700 system (Plasma-Therm, St. Petersburg, FL, USA) for 17 s at 20-mT pressure with chlorine flowing in at 30 sccm. Thereafter, the sample was soaked in PRS-3000 photoresist stripper (Mallinckrodt Baker, Phillipsburg, NJ,

USA) at 85 °C for 30 min and ultrasonicated for 120 s. Finally, the sample was rinsed first in IPA for 30 s and then in de-ionized water for 2 min, before being blow-dried with nitrogen. Two replicates of the sample were made simultaneously. Images of both replicates were collected on a Leo 1530 field-emission scanning electron microscope (FESEM) (Carl Zeiss, Oberkochen, Germany). Cross-sectional and top-view FESEM images of one replicate shown in Figs. 1(b) and (c) indicate that  $L = 600$  nm,  $\zeta = 5/12$ , and  $L_g = 91$  nm.

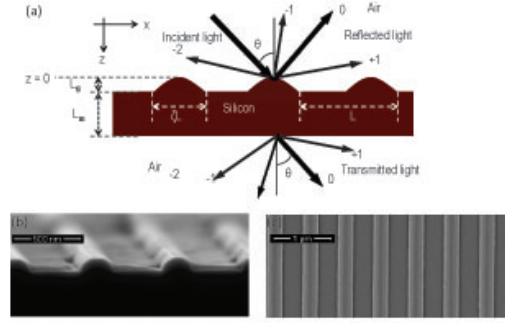


Figure 1: (a) Schematic representation of the experimental configuration used to excite the Uller-Zenneck wave. (b) Cross-sectional and (c) top-view FESEM images of one replicate of the fabricated sample with periodic corrugations;  $L = 600$  nm,  $\zeta = 5/12$ , and  $L_g = 91$  nm.

A custom-made variable-angle spectroscopic system was used to measure the specular reflectance  $R_p^{(0)}$  for  $\theta \in [7^\circ, 60^\circ]$  and  $\lambda_0 \in [400, 900]$  nm. In this system, the sample is mounted on a rotatable stage, and light from a HL-2000 tungsten halogen lamp (Ocean Optics, Dunedin, FL, USA) is passed through a GT10 polarizer (Thorlabs, Newton, NJ) before hitting the grating such that the incident magnetic field would be parallel to the grating lines. The specularly reflected light travels through a DH1M wire grid polarizer (Thorlabs) and is collected using a HRS-BD1-025 CCD spectrometer (Mightex, Pleasanton, CA, USA). The collection time was set at 10 ms. The following intensities of light were measured: (i)  $I_{\text{dark}}$  with the light source switched off and the sample absent; (ii)  $I_{\text{ref}}$  with the light source switched on and the sample absent; and (iii)  $I_p$  with the light source switched on and after specular reflection from the grating. The specular reflectance  $R_p^{(0)}$  was then computed as

$$R_p^{(0)} = (I_p - I_{\text{dark}}) / (I_{\text{ref}} - I_{\text{dark}}) . \quad (2)$$

The silicon wafer was extremely thick and so dissipative that  $T_p^{(n)} = 0 \forall n \in \mathbb{Z}$  for  $\lambda_0 \in [400, 900]$  nm, which was verified experimentally as well.

An ESW can be excited as a Floquet harmonic of order  $n$  by the  $p$ -polarized incident light when  $\theta = \theta_{\text{Can}}^{(n)}$ , where

$$\sin \theta_{\text{Can}}^{(n)} = \text{Re} \left\{ \sqrt{\varepsilon_s / (\varepsilon_s + 1)} \right\} - n\lambda_0 / L. \quad (3)$$

Theory indicates that the consequent signature of the excitation of the Uller–Zenneck wave is a sharp dip at  $\theta_{\text{Can}}^{(n)}$  in the plot of  $R_p^{(0)}$  versus  $\theta$  for constant  $\lambda_0$  [8]. The angles  $\theta_{\text{Can}}^{(n)}$  were calculated as functions of  $\lambda_0$ , with the wavelength-dependent values of  $\varepsilon_s$  provided in Fig. 2.

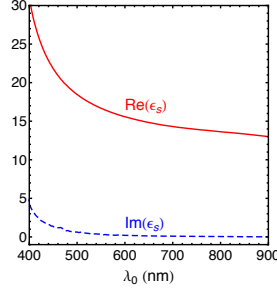


Figure 2: The real and imaginary parts of the relative permittivity  $\varepsilon_s$  of crystalline silicon [12] used for computations.

Figures 3(a) and (b) show  $R_p^{(0)}$  of the two replicates measured as functions of  $\theta$  and  $\lambda_0$ , while  $\theta_{\text{Can}}^{(n)}$  for  $n \in \{\pm 1, 2\}$  are plotted in Fig. 3(c) as functions of  $\lambda_0$ . A comparison of these figures clearly shows that the Uller–Zenneck wave is excited as a Floquet harmonic of

- (a) order 1 for  $7^\circ \leq \theta \lesssim 20^\circ$  and  $\lambda_0 \in [400, 560]$  nm,
- (b) order  $-2$  for  $20^\circ \lesssim \theta \lesssim 45^\circ$  and  $\lambda_0 \in [400, 570]$  nm, and
- (c) order  $-1$  for  $7^\circ \leq \theta \lesssim 31^\circ$  and  $\lambda_0 \in [600, 900]$  nm

Further confirmation was provided by RCWA calculations made with  $L = 600$  nm,  $\zeta = 5/12$ ,  $L_g = 91$  nm, and  $L_m = 27$   $\mu\text{m}$ . The silicon bump in every period of the grating was approximated as a part of a sinusoid. Figure 4 shows the calculated values of  $R_p^{(0)}$  and  $A_p$  as functions of  $\theta$  and  $\lambda_0$ . The sharp dips in the experimental plots of the specular reflectance [Figs. 2(a) and (b)] are mirrored as the sharp dips in the analogous theoretical plot [Fig. 4(a)] as well as the sharp peaks in the theoretical plot of the absorptance [Fig. 4(b)]. Parenthetically, the striations on the right sides of Figs. 4(a) and (b) occur due to Fabry–Perot resonances because  $\text{Im}(\varepsilon_s) \simeq 0$  for  $\lambda_0 \in [800, 900]$  nm.

Having thus experimentally confirmed the existence of the Uller–Zenneck wave, let us also speculate on a potential use of this phenomenon in the optical regime. For the interface of air and crystalline silicon, the phase speed  $v_p = k_0 c_0 / \text{Re}(q)$  and the propagation length  $\Delta_{\text{prop}} = 1 / \text{Im}(q)$  are plotted in Fig. 5 as functions of  $\lambda_0$ , where  $c_0$  is the speed of light in free space. Clearly,  $v_p > c_0$ , with the excess of  $v_p$  over  $c_0$  increasing to  $\sim 3.7\%$  at  $\lambda_0 = 850$  nm. At the same wavelength,  $\Delta_{\text{prop}} = 2.2$  mm, which is a significant distance in the context of silicon chips for microelectronics. Vertical-cavity surface-emitting lasers (VCSELs) commonly operate at  $\lambda_0 \sim 850$  nm, and can be modulated with frequencies in the GHz range [13, 14]. Thus,  $\sim 850$ -nm intra-chip optical interconnects could be enabled by the Uller–Zenneck wave. Regrettably, a similar strategy will not work for silicon photonics which operates in a spectral regime ( $\lambda_0 \gtrsim 1500$  nm) in which silicon has minuscule dissipation. But dissipation (i.e.,  $\text{Im}(\varepsilon_s) > 0$ ) is essential to the existence of the Uller–Zenneck wave.

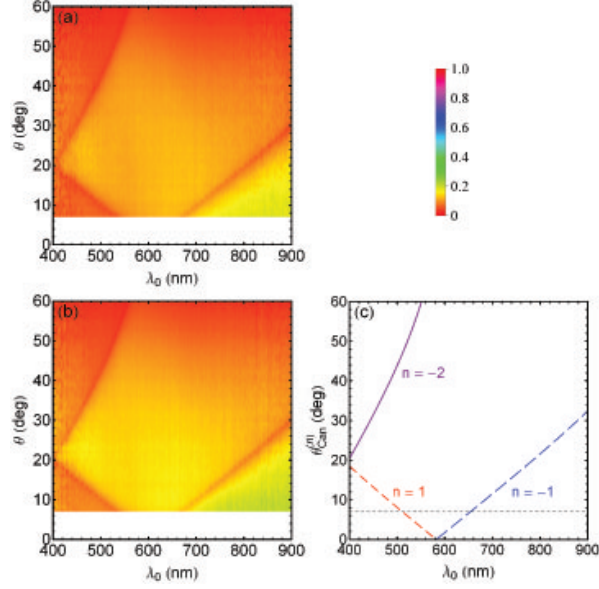


Figure 3:  $R_p^{(0)}$  of (a) the first and (b) the second replicates measured as functions of  $\theta$  and  $\lambda_0$ . (c)  $\theta_{\text{Can}}^{(n)}$  for  $n \in \{\pm 1, 2\}$  as functions of  $\lambda_0$ .

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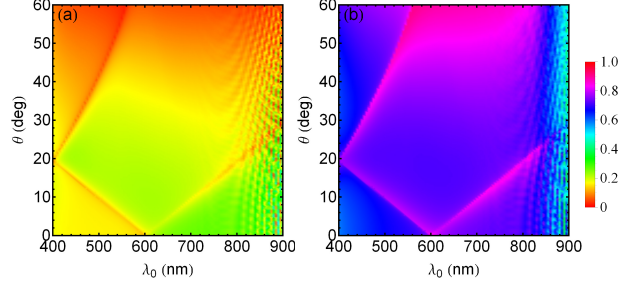


Figure 4: (a)  $R_p^{(0)}$  and (b)  $A_p$  calculated as functions of  $\theta$  and  $\lambda_0$  for  $L = 600$  nm,  $\zeta = 5/12$ ,  $L_g = 91$  nm, and  $L_m = 27$   $\mu\text{m}$ .

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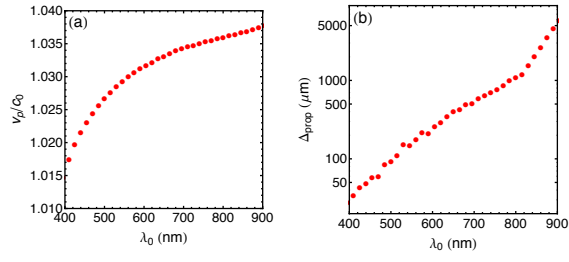


Figure 5: (a)  $v_p$  and (b)  $\Delta_{\text{prop}}$  calculated as functions of  $\lambda_0$ .